DOT/FAA/AR-99/7

Office of Aviation Research
Washington, D.C. 20591

Small-Engine Uncontained Debris Analysis

February 1999

Final Report

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U.S. Department of Transportation
Federal Aviation Administration

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Technical Report Documentation Page

1. Report No.
DOT/FAA/AR-99/7

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
SMALL-ENGINE UNCONTAINED DEBRIS ANALYSIS

5. Report Date
February 1999

6. Performing Organization Code
418300D

7. Author(s)
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8. Performing Organization Report No.

9. Performing Organization Name and Address
Naval Air Warfare Center, Weapons Division
Survivability Division
Systems Vulnerability Branch
China Lake, CA 93555-6001

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DTFA03-95-X-90019

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Aviation Administration
William J. Hughes Technical Center
Atlantic City International Airport, N.J. 08405

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code
ANE-110

15. Supplementary Notes
The William J. Hughes Technical Center COTR: Robert H. Pursel, AAR-432

16. Abstract

Under Contract to the Federal Aviation Administration, the Naval Air Warfare Center has conducted an analysis to define the characteristics of small civil turbine engine uncontained debris. The objective of the analysis was to define the debris size, weight, exit velocity, and trajectory that can be used to update AC 20-128A. The effort was conducted by gathering historical data from uncontained engine failures. These data included, when available, phase of flight, engine operating condition, the failed engine component, aircraft damage location, and damage size. With this basic information, debris size was correlated to damage size. A methodology developed in the "Large-Engine Uncontained Debris Analysis" report number DOT/FAA/AR-99/11 was used to estimate debris exit velocity. Representative engine cases and cowls were defined, and existing ballistic penetration equations were used to calculate debris exit velocity. This analysis was conducted for disk and blade failures on fan, compressor and turbine components.

Results of the analysis provided some interesting insight to these events. Looking at the debris trajectories, the analysis shows that the trajectories defined in AC20-128A are comparable to those seen in field events. Also the analysis highlights the fact that small engines produce fewer uncontained fragments than large engines (1 per event versus 11 per event on the average for large engines).

17. Key Words
Uncontained failure, Debris characterization, Debris database, Blade debris, Disk debris, Uncontained blade failure, Uncontained debris trajectory, Residual debris energy, Trajectory angles, Disk failure, Blade failure, Fan failure, Rim failure, BARRIER, Engine case penetration, Residual velocity, Damage ratio, Multiple debris

18. Distribution Statement
This document is available to the public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	18	

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EXECUTIVE SUMMARY

FAR/JAR 25.903(d)(1) states that "Design precautions must be taken to minimize the hazards to the airplane in the event of an engine rotor failure...." Minimization of the hazard to the airplane can be accomplished in several ways: (1) minimize the frequency of uncontained disc events; (2) minimization of fragment energies, quantities, and related trajectories; and (3) mitigation of the hazard to safe flight through mitigation provided in aircraft design and construction. It is understood that absolute containment is unlikely, thus the minimization of fragment energies and mitigation in the aircraft are the reasonable methods of compliance.

The Aviation Rulemaking Advisory Committee (ARAC) 25.903(d)(1) Task Group is in the process of updating the engine uncontained fragment hazard model as defined in Advisory Circular 20-128A. The updated model will be implemented in Advisory Circular 20-128B. The analysis defined herein is a significant part of that effort as it provides a methodology to define fragment energies and defines a generic engine fragment model. Additionally, some preliminary modeling of ballistic penetration of aircraft structures and potential barrier materials is presented.

INTRODUCTION

A small-engine uncontained engine debris analysis was conducted to define the debris trajectory, relative size, and exit velocity. Data for this analysis were provided by the small aircraft and engine manufacturers. Information for the analysis was provided in the form of worksheets which identified the engine type, failed component and, when available, relevant information about the uncontained debris and damage to the aircraft.

This information has been kept separate from the large-engine database and ongoing analysis efforts. Due to the limited information available, a similar level of analysis was not warranted.

EVENT SUMMARY

There were 40 separate events provided by the manufacturers to conduct the analysis. Within this data, ten incidents contain information on damage to the aircraft. Thirteen incidents include information on damage to the engine nacelle (one event contains information on both nacelle and aircraft damage). By component there is one fan disk event and five compressor events, but the majority of the events are turbine events, 34 out of 40 (table 1). Of the turbine events, 15 (44%) are rim events and 13 (38%) are disk events.

TABLE 1. EVENT SUMMARY

Event Types	Total	Blade	Rim	Disk
Fan	1	0	0	1
Compressor	5	1	3	1
Turbine	34	5	15	13
Total	40			

Six auxiliary power unit (APU) events are included in the analysis. A separate section, Auxiliary Power Units, is provided to discuss the containment aspect of the reported APU events.

SMALL ENGINES

TRAJECTORY ANALYSIS.

Of the 40 events, 17 had sufficient data to plot debris trajectory versus normalized damage length. Of these 17 events, 5 described damage to the aircraft. Four of the five reports described fuselage damage and one of the events denoted damage to a wing tip. Seven of the events define damage by providing a spread angle, i.e., ± 2 degrees (six to the nacelle, one to the fuselage). For these cases the fragment trajectories are shown with a spread bar.

The damage data was normalized to the failed component disk diameter or blade length respectively. Damage was correlated by failure type. In these cases, the failure type corresponds to the debris type that caused the damage. Data for turbine disk events defines the damage caused by the uncontained disk fragments. This is different than the analysis conducted on large engines where a disk failure caused the release of multiple blade fragments and the damage was

mostly cause by the blade fragments. For the small engines, the debris that was uncontained and caused damage to aircraft was almost entirely disk or disk rim fragments.

An overview of the available trajectory data is shown in figure 1. Data is shown for nacelle and fuselage damage. Trajectory angles are positive for forward trajectories and negative for aft trajectories. It is evident that nacelle damage is typically significantly larger than the failed component dimensions.

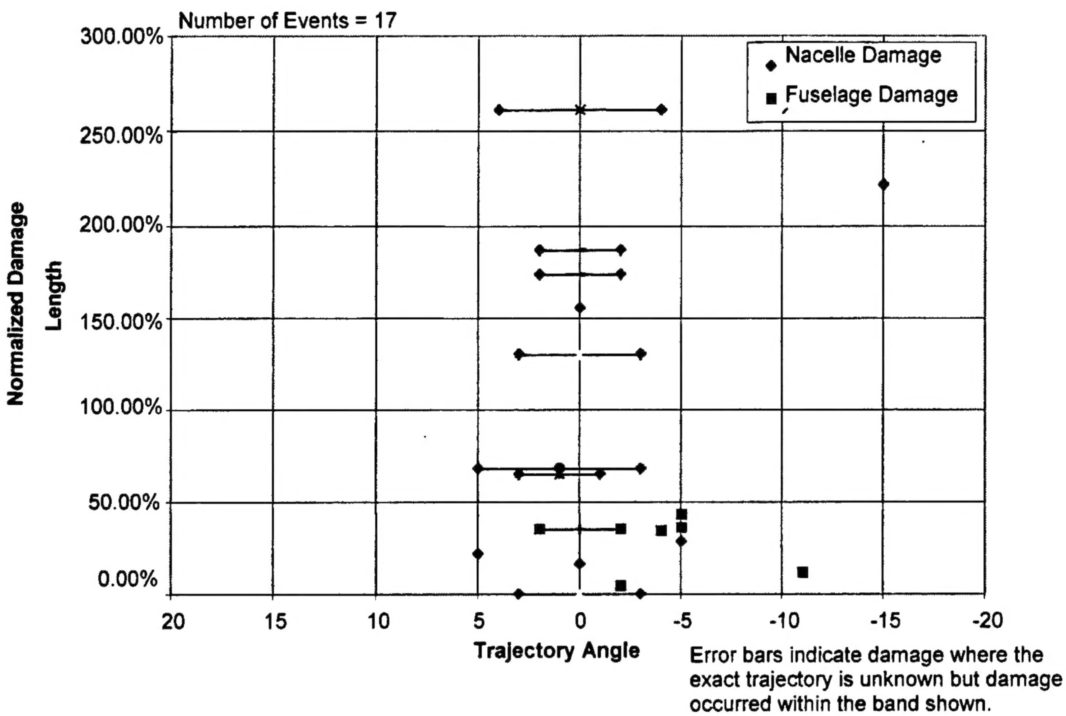

FIGURE 1. ALL EVENTS TRAJECTORY PLOT

FAN FAILURES. There is a single fan disk failure event recorded in the database. The full disk exited the engine nacelle. No report of aircraft damage was provided.

COMPRESSOR FAILURES. There are five incidents with compressor failures. Three of the events were rim failures with one blade and disk failure respectively. Damage and trajectory data are provided for two of the events (figure 2). Of these two events, one was a disk event (figure 3) and one was a rim event (figure 4). All of the damage was reported at a –5-degree trajectory angle. The damage ratio is less than 50% of the disk diameter in all cases.

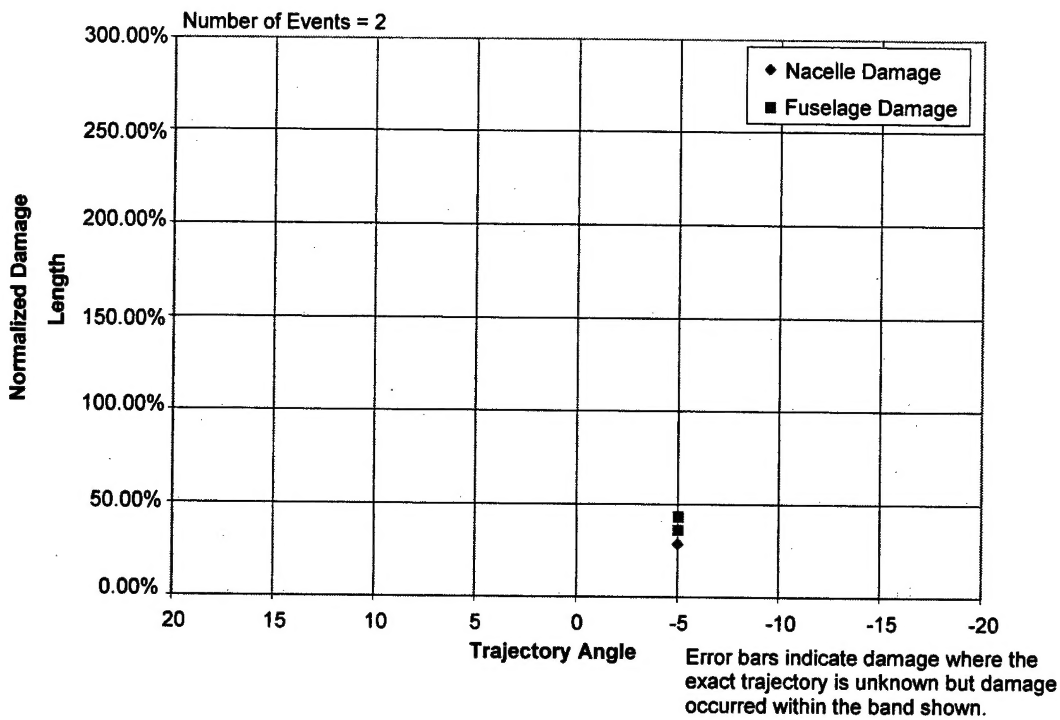

FIGURE 2. COMPRESSOR EVENTS TRAJECTORY PLOT

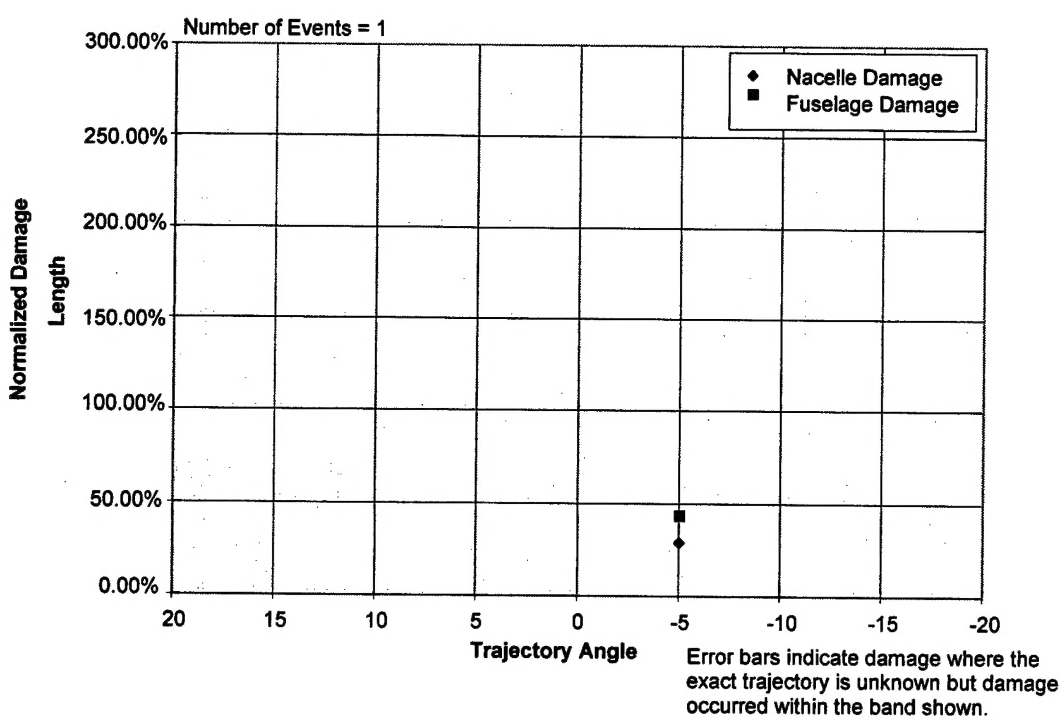

FIGURE 3. COMPRESSOR DISK TRAJECTORY PLOT

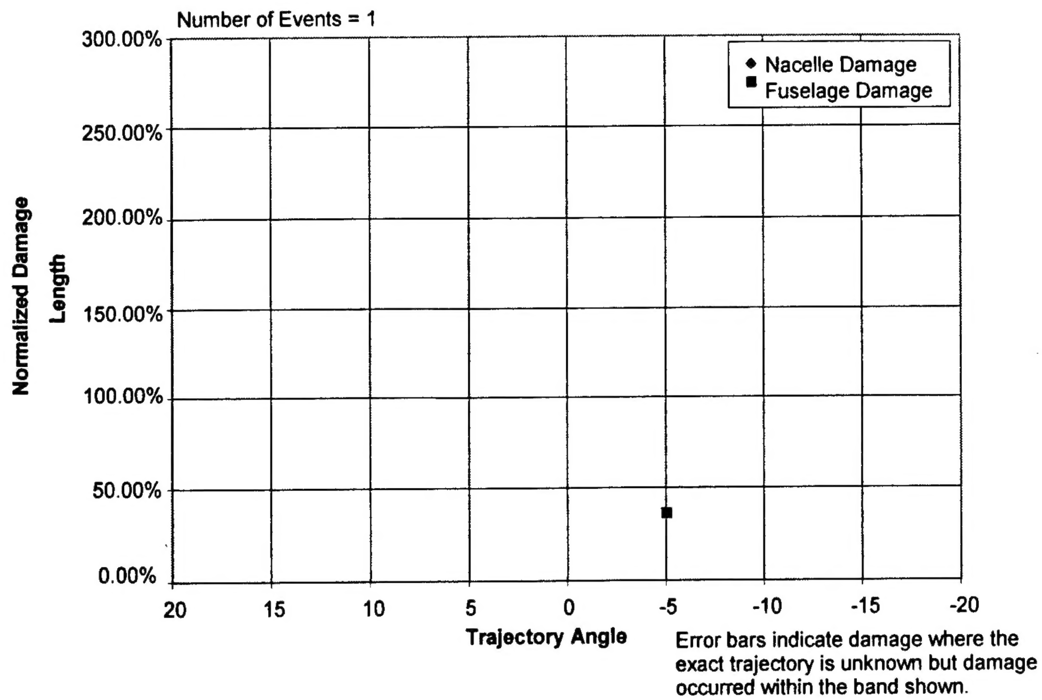

FIGURE 4. COMPRESSOR RIM TRAJECTORY PLOT

TURBINE FAILURES. The majority of the incidents reported were from turbine failures, 34 uncontained events. Fifteen were turbine rim failures, and 13 were turbine disk failures. Of the 34 events, only 15 reports contain trajectory and damage data (figure 5). Seven of these reports include the general forward and aft spread angle that the debris exited the nacelle. The majority of the data falls within a ± 5-degree spread angle. Damage to the nacelle has been reported as large as 2.60 times larger than the disk diameter. Fuselage damage was reported as less than 50% of the disk diameter in all cases. Trajectories for the debris damage to the nacelle ranged from 5 degrees forward to -15 degrees aft. Damage to the fuselage ranged from 2 degrees forward to -11 degrees aft.

Five turbine disk events were recorded with only one reporting damage to the aircraft fuselage (figure 6). In this case, damage was reported with a trajectory spread of ± 2 degrees. The trajectory spread for the turbine disk fragments is ± 4 degrees with an outlying point located at -15 degrees.

Nine turbine rim events were recorded, only one of which reported damage to the fuselage (figure 7). For this case, three damage locations were noted. The other events, for the most part, recorded trajectory data by noting a spread angle from damage on the nacelle. Fuselage damage for the rim segments ranged from -2 to -11 degrees. The damage size for the fuselage damage was less than 50% of the disk diameter. Nacelle damage spread angles ranged from 5 degrees forward to -3 degrees aft. Nacelle damage was as large as 1.73 times the disk diameter.

There is one reported event for turbine blade failure. In this event, damage was reported to the engine case only. No further information can be derived from this event.

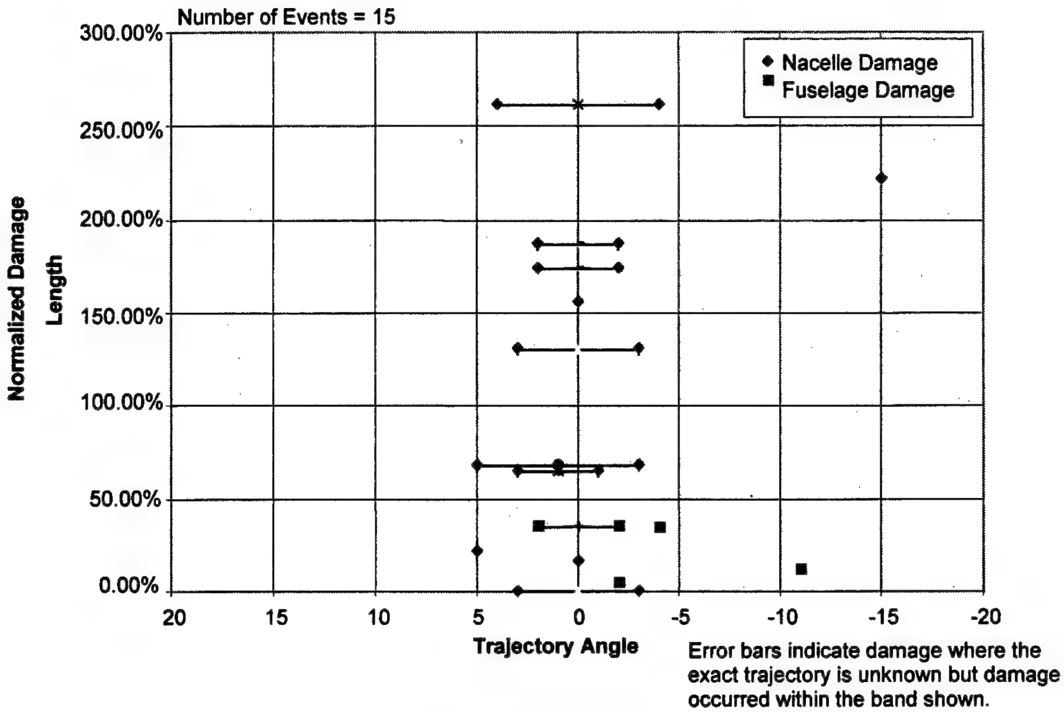

FIGURE 5. TURBINE EVENT TRAJECTORY PLOT

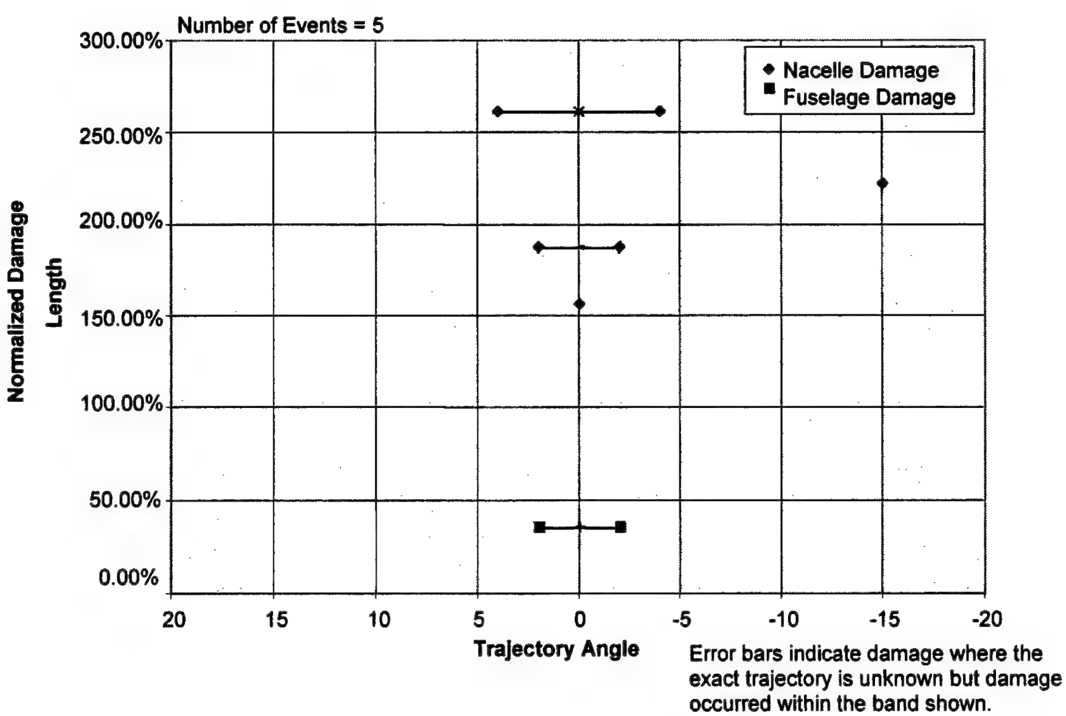

FIGURE 6. TURBINE DISK EVENT TRAJECTORY PLOT

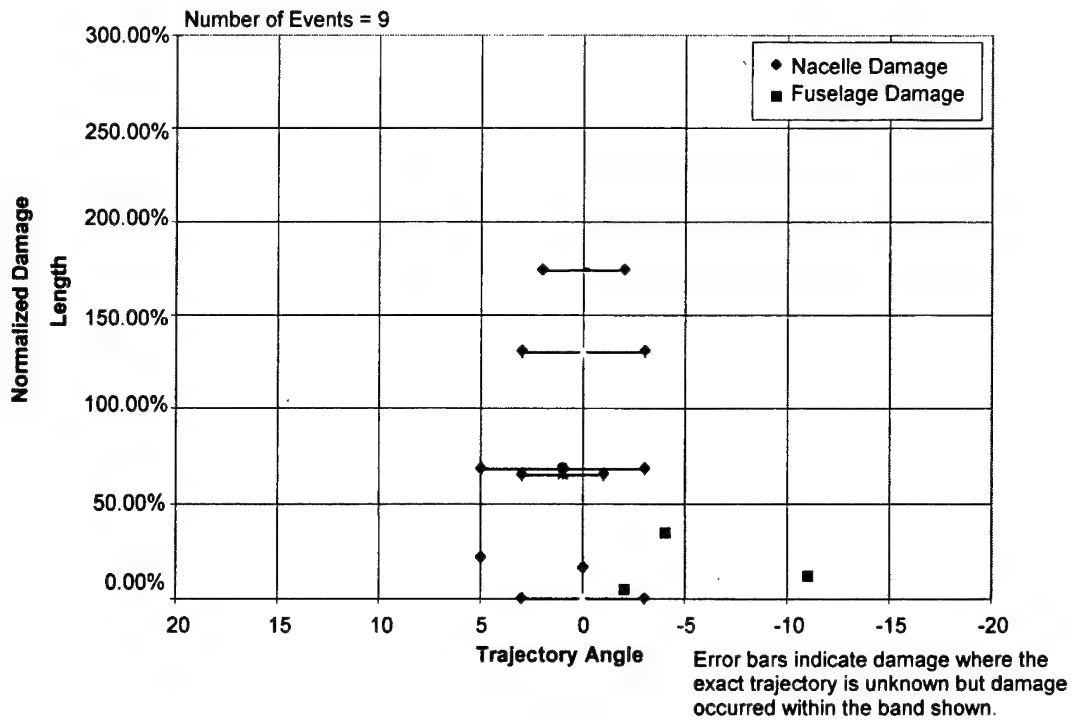

FIGURE 7. TURBINE RIM EVENT TRAJECTORY PLOT

DEBRIS CHARACTERISTICS.

Of the 40 events recorded, 25 contain data on the debris origin and size. A summary of the debris is provided in table 2. Table 2 provides some insight to the size of fragments for given engine components. It should be noted that this analysis is based on a limited amount of data.

TABLE 2. SMALL-ENGINE DEBRIS DATA SUMMARY

Debris Fragment Sizes					
	0% to 20%	20% to 50%	50% to 100%	> 100%	Totals
Fan Disk	0	0	1	0	1
	0.0%	0.0%	100.0%	0.0%	100%
Compressor Disk	0	2	1	0	3
	0.0%	66.7%	33.3%	0.0%	100%
Compressor Rim	0	2	1	1*	4
	0.0%	50.0%	25.0%	25.0%	100%
Turbine Disk	9	6	9	0	24
	37.5%	25.0%	37.5%	0.0%	100%
Turbine Rim	2	4	4	0	10
	20.0%	40.0%	40.0%	0.0%	100%

* Fragment size ratio was 1.06

DEBRIS SIZE.

Compressor Disk—1 Event. For compressor disks, two of the three fragments were within the 20 to 50 percent disk diameter size bin. The remaining fragment was in the 50% to 100% size bin. The average normalized length of the compressor disk fragments was 67% of the disk diameter (table 3). To select a fragment size that would capture most of the data, a 50% fragment size would include 66.7% of the compressor disk fragments.

Compressor Rim—3 Events. There were few compressor rim failures. Of the reported fragments, the normalized debris sizes were more or less split equally between the 20% to 50% bin and 50% to 100% bin. (The one fragment greater than 100% disk diameter was 106% and will be treated as 100%.) The average normalized debris size for compressor rim sections was 67% of the disk diameter.

Turbine Disk—8 Events. There was a fairly even split for turbine disk fragments from 20% to 100% of the disk diameter. The average turbine disk fragment was 54% of the turbine disk diameter. Reviewing the incident data, two events of the same engine disk type caused the 15 of the 16 fragments smaller than 50% of the disk diameter. The remaining events produced fragments in the 50% to 100% range. The average size of a fragment in the 50% to 100% bin is 85% of the disk diameter. This is very close to the length of a 1/3 disk fragment (86.6%).

Turbine Rim—10 Events. Eighty percent of turbine rim debris was larger than 20% of the disk diameter. The average normalized dimension is 39% of the disk diameter. Most fragments over 50% of the disk diameter are in the lower end of the size bin. And similarly, most fragments in the 20% to 50% bin were in the lower side of the size range.

Additional information on engine component dimensions and operating speeds were used to estimate the debris initial translational velocity and energy. For each of the categories, the normalized size, debris length, debris weight, initial velocity, and initial energy were calculated (table 3).

TABLE 3. AVERAGE DEBRIS CHARACTERISTICS

	Fan Disk	Compressor Disk	Compressor Rim	Turbine Blade	Turbine Disk	Turbine Rim
Normalized Size %	100	67	67	100	50	39
Length (in)	9.20	9.33	7.35	2.93	3.34	2.76
Weight (lb)	21.0	10.2	2.6	0.1	1.9	0.6
Initial Velocity (ft/sec)	Unknown	895.49	1688.02	990.60	883.24	932.56
Initial Energy (lb-ft)	Unknown	64394.70	100202.14	3231.98	19364.18	7205.67

For the most part, the average debris characteristics provide a good picture of the debris characteristics. The one exception as noted above is the turbine disk failures, where two events involving the same engine and the same disk design had a large number of small fragments which weighted the average to the small side. Removing those two events provides a broader

picture of the remaining six events. The result is an average normalized size of 87% of the disk diameter, as tabulated in table 4.

TABLE 4. TURBINE DISK CHARACTERISTICS

	Turbine Disk
Normalized Size %	87
Length (in)	7.18
Weight (lb)	6.3
Initial Velocity	791.79
Initial Energy	64754.78

PENETRATION ANALYSIS AND RESULTS. A penetration analysis was conducted to estimate the exit velocity of the uncontained debris from the engine nacelle. This analysis is conducted using the same model used in the large-engine debris study. The intent is to provide estimates of debris exit velocity and energy levels for the small-engine debris. Inputs for the model were based on the above average characteristics (except for the turbine disk debris as noted above). The following assumptions are used in the analysis.

1. The debris losses 75% of its initial velocity due to frictional effects internal to the engine. (This assumption was also used in the large-engine analysis for fan blade failures. It was derived from testing at Pratt & Whitney Engine.)

2. The debris penetrates two layers of casing and one layer of nacelle structure to determine the exit velocity. The engine designs reviewed typically have multiple cases and housings that the debris penetrates prior to exiting the engine.

   - Layer 1: 0.10-inch steel casing
   - Layer 2: 0.08-inch steel engine housing
   - Layer 3: 0.06-inch Al nacelle cowl

3. Turbine blade analysis assumes a hole is in the casing and housing. The initial penetration velocity is the same as the debris initial velocity. (Without this assumption, a single blade does not contain sufficient energy to exit the casing.)

The details of the penetration analysis are provided in figures 8 through 12. Results provided in the details are V_{50} a velocity for which a projectile would have 50% probability of penetration and perforating a certain thickness, for the plate debris residual velocity, residual energy, and the plate thickness (tr) required to stop the fragment at the given residual velocity. The results of the analysis (table 5) indicate that there is more than sufficient energy from most debris fragments to penetrate the fuselage structure of most small aircraft.

INPUTS	Compressor Disk								
Width	9.2	in							
Height	2	in							
Weight	10.2	lbm							
Release Velocity (V_r)	671	ft/s							
Obliquity	0	degree							
Plate	V_{50} (ft/s)	Release Velocity (ft/s)	Residual Energy (ft lbf)	tr (in)	Kinetic Energy Ratio	Delta Velocity (ft/s)	Plate Thickness (inch)	Fragment Angle (degree)	Material
1	146.8	623.4	61606.9	0.49	0.86	47.6	0.1	0	Hard Steel
2	119.9	588.1	54830.6	0.46	0.77	35.3	0.08	0	Hard Steel
3	45.3	580.1	53342.4	1.01	0.75	8.0	0.06	0	Aluminum 2024

FIGURE 8. COMPRESSOR DISK PENETRATION ANALYSIS

INPUTS	Compressor Rim								
Width	7.35	in							
Height	1	in							
Weight	2.6	lbm							
Release Velocity (V_r)	1266	ft/s							
Obliquity	0	degree							
Plate	V_{50} (ft/s)	Release Velocity (ft/s)	Residual Energy (ft lbf)	tr (in)	Kinetic Energy Ratio	Delta Velocity (ft/s)	Plate Thickness (inch)	Fragment Angle (degree)	Material
1	238.4	1152.6	53677.0	0.57	0.83	113.4	0.1	0	Hard Steel
2	194.7	1068.7	46147.1	0.52	0.71	83.9	0.08	0	Hard Steel
3	71.6	1048.5	44418.1	1.17	0.69	20.2	0.06	0	Aluminum 2024

FIGURE 9. COMPRESSOR RIM PENETRATION ANALYSIS

INPUTS	Turbine Blade								
Width	2.93	in							
Height	1	in							
Weight	0.1	lbm							
Release Velocity (V_r)	990	ft/s							
Obliquity	0	degree							
Plate	V_{50} (ft/s)	Release Velocity (ft/s)	Residual Energy (ft lbf)	tr (in)	Kinetic Energy Ratio	Delta Velocity (ft/s)	Plate Thickness (inch)	Fragment Angle (degree)	Material
1	776.7	508.4	401.7	0.06	0.26	481.6	0.1	45	Aluminum 2024

FIGURE 10. TURBINE BLADE PENETRATION ANALYSIS

INPUTS	Turbine Disk								
Width	7.18	in							
Height	1	in							
Weight	6.3	lbm							
Release Velocity (V_r)	593.8	ft/s							
Obliquity	0	degree							
Plate	V_{50} (ft/s)	Release Velocity (ft/s)	Residual Energy (ft lbf)	tr (in)	Kinetic Energy Ratio	Delta Velocity (ft/s)	Plate Thickness (inch)	Fragment Angle (degree)	Material
1	99.5	567.4	31518.5	0.68	0.91	26.4	0.1	0	Hard Steel
2	81.3	547.6	29361.0	0.66	0.85	19.8	0.08	0	Hard Steel
3	30.5	543.1	28873.2	1.46	0.84	4.6	0.06	0	Aluminum 2024

FIGURE 11. TURBINE DISK PENETRATION ANALYSIS

INPUTS	Turbine Rim								
Width	2.76	in							
Height	1	in							
Weight	0.6	lbm							
Release Velocity (V_r)	699	ft/s							
Obliquity	0	degree							
Plate	V_{50} (ft/s)	Release Velocity (ft/s)	Residual Energy (ft lbf)	tr (in)	Kinetic Energy Ratio	Delta Velocity (ft/s)	Plate Thickness (inch)	Fragment Angle (degree)	Material
1	402.8	506.4	2390.8	0.13	0.52	192.6	0.1	0	Hard Steel
2	329.9	349.1	1136.1	0.09	0.25	157.3	0.08	0	Hard Steel
3	117.5	319.8	953.9	0.18	0.21	29.2	0.06	0	Aluminum 2024

FIGURE 12. TURBINE RIM PENETRATION ANALYSIS

TABLE 5. PENETRATION SUMMARY

	Compressor Disk	Compressor Rim	Turbine Blade	Turbine Disk	Turbine Rim
Normalized Size %	67	67	100	87	39
Length (in)	9.33	7.35	2.93	7.18	2.76
Weight (lb)	10.2	2.6	0.1	6.3	0.6
Exit Velocity (ft/sec)	580	1048	508	543	319
Exit Energy (lb-ft)	53342	44518	401	28873	953

AUXILIARY POWER UNITS

Six APU events were provided for the analysis. Trajectory data were unavailable for these events. The data provided for APUs do not support a trajectory-penetration analysis as described in this document. A summary of each of the events is provided in table 6. The summary includes failed component, debris size, engine operating speed, estimated translational velocity and energy, and damage summary.

TABLE 6. APU EVENT SUMMARY

Incident No.	Date	Component	Type	Normal Length (%)	Weight (lb)	Rotor Speed (rpm)	Initial Velocity (ft/s)	Initial Energy (lb-ft)	Damage Summary
35	3/29/91	T	D	100	9.1	35314	677	64979	APU starter motor dented and aircraft compartment structure torn. Debris contained within aircraft structure.
				80	18.3	35314	1354	519830	Containment plate torn and dented. Debris contained within aircraft structure.
36	11/22/90	T	D	100	13.7	63830	836	148181	Debris contained within APU.
				100	8.6	63830	947	120208	Debris contained within APU.
					1.8	63830	184	948	Debris exited APU and dented aircraft skin.
					1.8	63830	184	948	Debris exited APU and dented aircraft skin.
37	10/20/91	C	B						- Compressor shaft damaged inlet screen and damaged the inlet vanes. - Maintenance door dented. - Hole in compartment fire wall.
38	12/14/91	C	R	32	1.2	63830	2155	87994	
				43	1.6	63830	2147	115939	- Scroll housing fractured. No aircraft system effect. - Compressor shaft damaged inlet housing, APU plenum damaged, and RH firewall penetrated.
39	3/28/92	C	R	106	5.0	63830	1395	151063	- APU diffuser vanes torn and scroll penetrated. - Compressor shaft was liberated and tore the firewall and left a cut in the aircraft skin.
40	4/00/91	T	D						Entire disk exited the APU through the exhaust duct and came to rest 200 m behind the aircraft. No noted damage to the aircraft.

C- Compressor, T - Turbine, D - Disk, R - Rim, B - Blade

CONCLUSIONS

DEBRIS SIZE AND TRAJECTORY.

Keeping in mind the limited amount of data in the analysis, the following conclusions are provided. (See table 7.) There is insufficient data to define fan disk debris characteristics. Compressor disk debris characteristics are based on the average characteristics of the data within the database. The trajectory spread is based on damage to the aircraft and nacelle. Due to the

limited amount of data, the trajectory angle was extended to include +5 degrees forward to -5 degrees aft. The compressor rim characteristics were derived using the same reasoning and logic. Turbine disk characteristics were defined based on six of the eight turbine disk events.

TABLE 7. SMALL-ENGINE DEBRIS CHARACTERIZATION SUMMARY

Component	Normalized Size	Length (in)	Mass (lb)	Exit Velocity (ft/s)	Trajectory Spread
Fan Disk	--	--	--	--	--
Compressor Disk	67%	9.3	10.2	895	$\pm 5^{\circ}$
Compressor Rim	67%	7.4	2.6	1688	$\pm 5^{\circ}$
Turbine Blade	100%	2.93	0.1	508	--
Turbine Disk	87%	7.2	6.3	543	$+ 5^{\circ}$ to -15°
Turbine Rim	40%	2.8	0.6	320	$+ 5^{\circ}$ to -11°

AUXILIARY POWER UNITS.

The APU debris sizes are comparable to those of small thrust-producing engines; however, the damage associated with the debris is not consistent. In most cases it is components other than the failed component that damage the aircraft skins. In these cases, the damage is typically a small puncture in the aircraft skin or firewall. In thrust-producing engines, a small puncture in the engine nacelle is not considered an uncontained failure if the debris does not exit the engine nacelle. The most common damage to the aircraft was from the compressor shaft which became unrestrained after a compressor failure. Eliminating this failure mode would eliminate half of the events provided for analysis.